Special Issue: Earthquake geology

Earthquake geology: science, society and critical facilities

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1. Introduction - Earthquake geology, Earthquake Environmental Effects (EEE) and seismic hazard assessment

Earthquake geology studies the effects, the mechanics and the impacts of earthquakes in the geological environment. Its role is also to decode the fault history, therefore its approach is fault specific and its outcomes are of decisive value for seismic hazard assessment and planning. The term Earthquake geology includes aspects of modern instrumental studies, tectonics and structural geology, historical surface deformation and tectonic geomorphology, whereas paleoseismology is considered part of earthquake geology [McCalpin 2009]. In a broader sense, paleoseismology intends to establish the seismic history of a given fault or given region from deformed sediments or rocks, beyond the limited temporal resolution of instrumental and historical seismicity [e.g., Audemard and Michetti 2011]. The advances of Earthquake geology and paleoseismology over the last few decades offered a quantitative description of Earthquake Environmental Effects that led to the development of the Environmental Seismic Intensity Scale ESI 2007 [Michetti et al. 2007].

Seismic hazard assessment is predominantly based on the instrumental and historical catalogues of seismicity. However, these catalogues are incomplete and have an inhomogeneity of geographical and temporal coverage in terms of the seismic record, forming their main disadvantage. This is because historic catalogues are generally too short (from several tens of years to several hundreds of years, depending on the country) compared to the recurrence interval of particular faults (ranging from a few hundred years to several thousands of years) [Goes 1996, Yeats and Prentice 1996, Machette 2000, Valensise and Pantosti 2001]. The latter implies that the sample from the historical record is incomplete and that a large number of faults would not have ruptured during the completeness period of the historical record. For example, Greece has one of the longest historical catalogues worldwide with the oldest recorded events in 550 B.C. However, this catalogue is considered complete for events M≥7.3 since 1500 and for M≥6.5 only since 1845 [Papazachos et al. 2000]. In addition, maps based on historical seismicity can give erroneous pictures of the present day hazard. A low seismicity zone on such a map, representing low hazard, may delineate a seismic gap (i.e., a gap that an impeding earthquake will cover) and actually be a place of high present and future hazard [Scholz 2002]. On the other hand, a region that has recently experienced a damaging earthquake, and hence is represented as high hazard on a map, actually may be a region of low hazard in the near future because it is now at an early stage in a new seismic cycle [Scholz 2002].

Geological data have the potential to extend the history of slip on a fault back many thousands of years, a time span that generally encompasses a large number of earthquake cycles [Yeats and Prentice 1996], and thus elucidates the long-term pattern of fault-slip. As a result, fault specific approaches are becoming very important for seismic hazard assessment, by providing quantitative assessments through measurement of geologically recorded slip on active faults, sampling much greater periods of time and providing a more reliable estimate of hazard than the historical earthquake record [e.g., Yeats and Prentice 1996, Michetti et al. 2005]. In addition, geologic fault slip-rate data offer complete spatial coverage, providing higher spatial resolution than traditional seismic hazard maps based on historical/instrumental records [Boncio et al. 2004, Roberts et al. 2004, Pace et al. 2010, Papanikolaou et al. 2013]. For land-use planning and critical facilities or insurance risk evaluation purposes, a higher spatial resolution is also desirable.

During the last years, a number of major earthquakes and mega-earthquakes occurred at plate boundaries, which were in most of the cases oversized in relation to the data provided by the historical and instrumental seismicity. The Haiti Mw 7.0 (Haiti, January 2010), Maule Mw 8.8 (Chile, May 2010), and Tōhoku Mw 9.0 (Japan, March 2011) events caused widespread devastation and claimed hundreds of thousands of lives. Beside these mega-quakes, several moderate events had surprisingly dramatic consequences. The L'Aquila, Mw 6.3 (Italy, April 2009), Christchurch Mw 6.3 (New Zealand, February 2011), Lorca Mw 5.1 (Spain, May 2011), Emilia-Romagna Mw 5.9 and Mw 5.7 (Italy, May 2012), and Tabriz Mw 6.4 and Mw 6.3 (Iran, August 2012) events showed strong ground motions and caused rockfalls, landslides, liquefaction, and other types of EEEs. Combined with relatively low building standards, these moderate quakes could also pose a high local hazard, due also to their high recurrence rate. However, the Christchurch example showed that even good to excellent building standards cannot prevent a large number of damages. An unfavorable local setting like the presence of a deep sediment basin or geometric peculiarities may lead to an amplification of the seismic waves, resulting in extraordinary strong ground motions [Smyrou et al. 2011].

Moderate events have illustrated that ground motion may not be the most important agent of destruction. Earthquake Environmental Effects like liquefaction, landslides and rockfalls may locally cause far more damage, and should be taken into account in any comprehensive assessment of seismic and associated hazards. This makes clear that the use of macroseismic scales that depend almost solely on damage to man-made structures may obscure the consequences of an earthquake event and can lead to an underestimation. Overall, traditional intensities from which attenuation laws are extracted are based on human parameters. Therefore, when using the effects on humans and human environments to assess the macroseismic intensity, intensity will tend to reflect mainly the economic development and the cultural setting of the area that experienced the earthquake, instead of its "strength" [Serva 1994]. On the other hand, Earthquake Environmental Effects are not influenced by human parameters. The Environmental Seismic Intensity Scale ESI 2007, introduced by INQUA, incorporates the advances and achievements of Earthquake geology and evaluates earthquake size and the epicentral intensity solely from the Earthquake Environmental Effects [Michetti et al. 2007, Reicherter et al. 2009].

The ESI 2007 has been tested in several countries and tectonic settings. There are already more than 25 publications regarding the scale and more than 100 tested events. The scale has been tested both in moderate (e.g., 1998 Mw=5.6 Slovenia; Gosar [2012]) and catastrophic events (e.g., Mw=7.9 2008 Wenchuan earthquake, China; Lekkas [2010]), demonstrating its increasing value and accuracy towards the highest levels of the scale, where traditional scales saturate [Michetti et al. 2004]. The comparability of recent quakes to historical and paleoevents is also not guaranteed, but the ESI 2007 allows the comparison among future, recent and historical earthquakes since the building environment is not considered. Therefore, the use of the ESI 2007 scale, based on EEEs, may help to overcome this problem. Currently there is an increasing number of studies that compare the ESI 2007 scale with traditional macroseismic scales for recent events [e.g., Papathanassiou and Pavlides 2007, Porfido et al. 2007, Ota et al. 2009]. Such a comparison can offer valuable info regarding the vulnerability of the buildings [e.g., Guerrieri et al. 2009]. Once more and more data are available it will be possible to identify cases in which the two types of scales lead to similar results and settings with differing intensity estimations. A re-appraisal of historical and recent earthquakes so as to constrain the ESI 2007 scale and the extraction of ESI-based attenuation laws may prove beneficial for seismic hazard assessment by reducing the large uncertainty implied in the attenuation laws and eventually in seismic hazard maps [Papanikolaou 2011]. As more data from recent and historical events are gathered, the compilation of an ESI 2007 attenuation relationship should be one of the future goals for seismic hazard assessment. Overall, it is interesting to note that the concept of the ESI 2007 has now been followed in Earthquake Archaeological Effects (EAE) [Rodríguez-Pascua et al. 2011] and the newly introduced Integrated Tsunami Intensity Scale (ITIS-2012) [Lekkas et al. 2013].

Transporting this knowledge to paleoseismological studies is important for detailed insights into the earthquake history and the earthquake behavior of the faults that pose a hazard to society. There is an ongoing debate about how faults do evolve over time and how they react on stress changes in their local and regional seismotectonic context. It is not clear if the model of characteristic earthquakes is valid, invalid at all or only true for certain areas and settings [e.g., Stein et al. 2012]. For the incorporation of paleoseismological data into seismic hazard assessments these questions need to be answered. The studies presented in this special volume contribute to this goal.

2. The work included in this volume

After the very successful 1st Workshop on Earthquake archaeology and paleoseismology held in the archaeological site of Baelo Claudia (Spain, 2009), the

INQUA Focus Group on paleoseismology and active tectonics decided to support this joint initiative with the IGCP-567 "Earthquake archaeology". The second joint meeting was held in the Gulf of Corinth (Greece), a tectonically active area within the Africa-Eurasia collision zone and located in the origins of the pioneer's works on archeoseismology. Aim of the meeting was to stimulate the already emerging comparative discussion about Earthquake Environmental Effects and Earthquake Archeoseismological Effects in order to elaborate comprehensive classifications for future cataloguing and parametrization of ancient earthquakes and paleoearthquakes. Another focus was to discuss how the EEE-based ESI 2007 macroseismic intensity scale can be compared with traditional macroseismic scales that rather focus on man-made structures for earthquake intensity assessment. In this workshop a multidisciplinary and cross-disciplinary program was presented, illustrating that there is an urgent necessity to share the knowledge and objectives among geologists, seismologists, geodesists, archaeologists and civil engineers in order to improve seismic hazard assessments and analyses in near future.

This special volume "Earthquake geology: science, society and critical facilities" is an outcome of the Corinth 2011 conference. It includes 14 papers, mainly by early career researchers (ECRs), that deal with paleoseismology, active tectonics, tectonic geomorphology and macroseismic intensity scales (ESI 2007, EMS 98). Geographically, the papers clearly focus on southern Europe, or more precise, on the area affected by the stress resulting from the African-European collision (Figure 1).

More than half of the studies were conducted on the Balkan Peninsula, two each in Iberia and at the Azores archipelago, one in Italy and one in Slovenia.

Alexopoulos et al. combined near surface geophysical investigations with remote sensing data at the spectacular Meteora site in central Greece, where tectonic deformation is strongly influencing groundwater flow. The authors identified tectonic discontinuities on the surface, related them with subsurface electrically conductive zones within the conglomerate strata that are interpreted as groundwater flow paths and demonstrated how future seismic events might interrupt these spatially sensitive hydraulic connections. This work is especially important for understanding the physics behind the hydrological anomalies that are classified as EEEs in hard rocks.

A large sediment core from the Gulf of Corinth was studied by **Campos et al.** They found a series of homogenites and turbidites both in lacustrine and marine environments in this rapidly expanding rift in central Greece. 38 turbidites are interpreted to have possible seismic origin, and recurrence intervals for the events were determined. This study presents rare offshore data which can be correlated to the on-shore investigations of the active faults in that area, which belong to the fastest moving tectonic structures in Europe.

Carmo et al. investigated escarpments on São Miguel Island, Azores, Portugal. The authors trenched across these structures and found evidence for the neotectonic activity of the Altiprado Faults. They identified a number of surface rupturing events, some of which occurred in historical times. A comparison with available

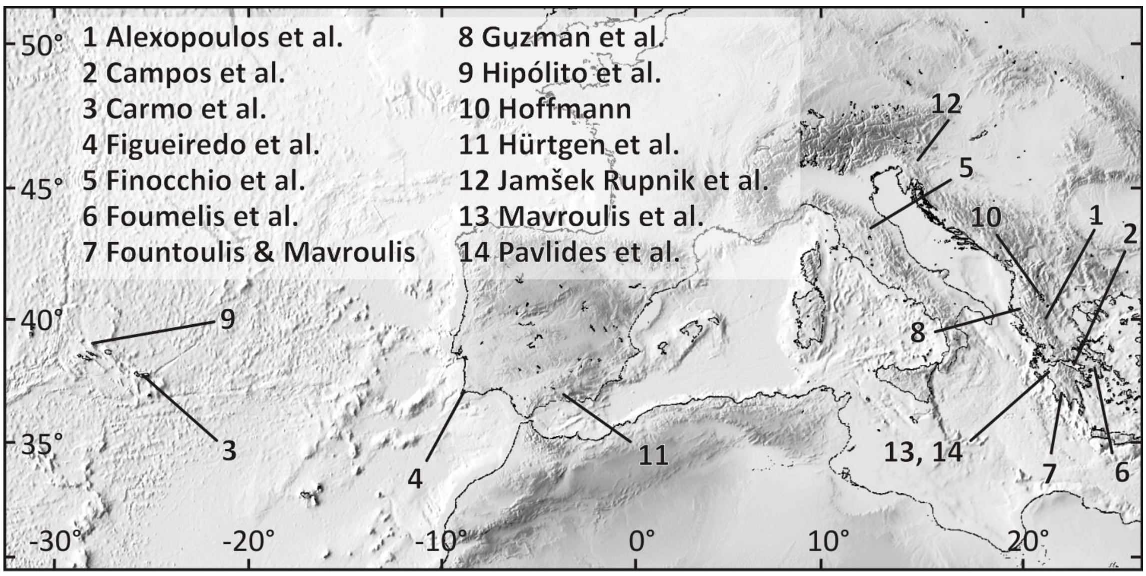

Figure 1. The study sites of the papers included in this special volume.

data from written sources led them to assign one event to the deadly earthquake from 1522, which reached intensities X in its epicentral area. According to the trenching data, the quakes on São Miguel Island might typically reach magnitudes between 5.7 and 6.7. This study sheds light on the seismic hazard of a region which is normally thought to be dominated by volcanic hazards.

Despite the fact that no or only minor seismic activity is ascribed to SW Portugal, the region yields a moderate seismic hazard due to offshore seismic sources. **Figueiredo et al.** investigated Pleistocene marine terraces along the coast of Europe's southwesternmost tip in order to determine the rate of tectonic uplift and to find out whether major offshore events like the 1755 Lisbon earthquake led to significant morphological changes onshore. By mapping and dating several terraces and considering the sea level fluctuations, the authors were able to determine a long-term uplift rate of 0.1-0.2 mm/yr.

The relation of the low-angle Altotiberina fault in central Italy to other faults in this area is highly debated. **Finocchio et al.** use a 2D finite-element model to investigate the interseismic deformation of this structure and compared the results with geodetic velocities, stress orientations and geological data. This paper presents important insights into the structure of this major fault zone and its rheology in a regional context. The data help to understand fault interaction and the locked state of faults.

The Athens Basin in Greece is not only home to millions of people, but is also surrounded by several active normal faults. The geometry and the activity of these faults are thought to be controlled by a large detachment zone, separating structures with different strike and different slip rates. **Foumelis et al.** are able to show by the means of a GPS-derived velocity field that the detachment, despite being inactive since Pliocene times, clearly controls the strain in the area. This is the first study to quantify this effect on the deformation pattern in this area.

The seismic hazard of the Peloponnesus Peninsula in Greece is not only related to the offshore Hellenic Arc, but a number of strong historical events are proven onshore, too. The 1986 Kalamata earthquake caused 20 fatalities and led to the destruction of numerous houses. The event also left its imprints in the landscape - **Fountoulis and Mavroulis** reviewed the earthquake environmental effects of the quake using the ESI 2007 macroseismic intensity scale. They conclude on a maximum intensity of IX and found that this value is in agreement with other macroseismic scales. Furthermore, the authors related their observations to the active faults of the study area and concluded on the use of the ESI 2007 scale for future seismic hazard assessments.

Guzman et al. investigated marine river terraces in southern Albania. They aimed on the determination of vertical slip rates of the main active structures in the Dinaric-Hellenic Alpine fold belt. Geomorphological mapping and regional correlation of terraces revealed shifts in the incision rates of rivers and the authors were able to determine slip rates for eight faults during the last 19 kyrs.

Hipólito et al. investigated outcrops on Graciosa Island, Azores, Portugal, in order to analyze how the seismicity of this volcanic island fits into the regional stress regime. The authors identified two main fault structures on the island which are not compatible with a single stress regime and, thus, postulate alternating stress fields. These fields are dominated by the spreading of the Atlantic and an interplate shear zone and the results indicate that the Azores Islands undergo time-variable deformation in a wide zone. This paper is a great example for how local outcrop geology, regional deformation analysis and seismicity data can help to reveal the geodynamic context of a study area in a complex tectonic setting.

The seismic landscape of Lake Ohrid in FYROM and Albania is analyzed by **Hoffmann**. She conducted topographic profiling across prominent scarps to investigate the slip rates of the main faults and the tectonic evolution of the basin. Her results show that the idea of all these scarps being post-glacial comes along with geometrical problems - some scarps are much higher than they could possibly be and scarp heights vary significantly across single faults. The author discusses possible explanations and suggests that gravitational movements, among other effects, must be taken into account when deducing slip rates from post-glacial scarp heights.

The Granada Basin in southern Spain is one of the tectonically most active regions on the Iberian Peninsula, characterized mainly by normal faults. Historic seismicity is well-documented, but the activity of some of the most important faults remains unclear. **Hürtgen et al.** conducted field work and GIS analyses for a morphotectonic study of the Padul-Nigüelas Fault Zone. This approach takes the concept of seismic landscape [Michetti et al. 2005] to the quantitative level. They found a differentiation in the state of activity along the fault zone and discuss the importance of the input parameters for such a type of analysis.

The slip rates and offsets of thrust faults are often hard to be directly investigated in the field. Scarps in Quaternary sediments close to the Slovenian capital were ascribed to the movement of thrust faults by **Jamšek Rupnik et al.** The authors dated sediments with OSL and ISL and were able to determine slip rates of these faults during the last 133 ka. The data reveal maximum expectable magnitudes of around 6.0-6.5, which clearly illustrates the contribution of these faults to the regional seismic hazard in this densely populated and economically important area.

On June 8, 2008, a moderate strike slip earthquake occurred in Andravida, NW Peloponnesus, Greece. Two papers investigate the environmental effects of this event. **Mavroulis et al.** applied the ESI 2007 scale and compared their findings to the EMS-98 scale. No primary earthquake environmental effects were recorded, but secondary effects yield intensities of VIII-IX. While in cases where intensity VIII was recorded both scales agree, they strongly differ elsewhere. Generally, ESI intensities are found to be one or two degrees lower than EMS intensities. The authors conclude that not only the building standards, but also the local geology plays a major role in the damage distribution.

Pavlides et al. focused on mass movements and liquefaction triggered by the same quake on the Peloponnesus. They present data from a post-event survey and mapped the liquefaction-prone areas. A rockfall hazard zonation for the Andravida region was developed using the shadow-angle method. Both studies show how earthquake damage and environmental effects are controlled by local soil and rock properties and that directional effects play an important role in their distribution.

This volume is dedicated to the memory of the Associate Professor Ioannis Fountoulis (1954-2013) who passed away too early. Prof. Fountoulis was a structural geologist, member of the National and Kapodistrian University of Athens, working since the 80s in Neotectonics. He participated in several INQUA meetings and workshops, including the Corinth 2011. He contributed in 3 separate papers within this volume, but sadly passed away before its publication.

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